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Work completed under Grant # AFOSR-88-0024 during the time period 1 October 1987 through 28 February 1991 is reported. Topics include the theory of neural networks and fundamental properties of optical interconnections. Publications funded in whole or in part by the grant are also listed.

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FINAL REPORT

Grant #AFOSR-88-0024

Joseph W. Goodman, Principal Investigator

Information Systems Laboratory

Stanford University

Stanford, California 94305

April 30, 1991

1.0 Introduction

This report summarizes the work accomplished under Grant # AFOSR-88-0024 during the time period 1 October, 1987 through February 28, 1991. The summary presented here is a brief one. The details of the results can be found in the many publications that resulted from the work supported here.

The work carried out fell in two specific areas: 1) Theory of neural networks, and 2) Fundamental properties of optical interconnections. Two students received their Ph.D.'s under this support, one in each area. We summarize the results in each of these areas in what follows.

2.0 Theory of Neural Networks

The work in this area was purely theoretical, and focused on fundamental properties of the Hopfield network. The Ph.D. student responsible for this work was Jehosua Bruck, who is now working at the IBM Almaden Research Laboratory. Particular results fell in several different sub-areas, as now described.

2.1 Hopfield Network as an Associative Memory

- We demonstrated that the capacity of the Hopfield network as an associative memory is extremely limited. For example, it is impossible to store and successfully retrieve two vectors at Hamming distance 1. For vectors having a Hamming distance greater than 1, the maximum storage capacity is less than 4 vectors.
- We demonstrated that the network should be fully connected. There are some very simple tasks that the network can not perform if it is not fully connected.
- We demonstrated that mappings that contain a sphere (such as the decoder for a Hamming code) can not be realized by such a network.
- We showed that the outer product method for programming memory can result in many (exponential in the number of words we wish to store) spurious states.

2.2 Hopfield Network for Performing "Hard" Computations

- We showed that even if we let the network run for an exponential time, we still need an exponential number of neurons to solve a hard (NP complete) problem. This conclusion is also true if we are satisfied to obtain an approximate solution, as opposed to an exact solution.

2.3 What Problems is the Hopfield Network Well-Suited For?

- Optimization problems must be mapped to the network by formulating them as a maximization of a set of quadratic forms that are coupled by heuristically determined coefficients.

- Finding the global maximum of the energy function associated with the network running in a serial mode is equivalent to finding the minimum cut in the undirected graph associated with the network.
- The maximum likelihood decoding problem for linear block codes is equivalent to finding the global maximum os the energy function of a network that can be constructed knowing the generator matrix of the code.
- Given a linear block code, a network can be constructed using the parity check matrix, such that every stable state of the network corresponds to a codeword and every codeword corresponds to a stable state, thus solving the "programming" problem for linear codes.

2.4 Can the Power of Such Networks be Increased by Increasing the Complexity of an Individual Neuron?

- Normally neurons are considered to be simple linear threshold devices. If they are increased in complexity to be polynomial threshold devices, does the power of the network increase? The answer is that not much is gained. A two layer network of linear threshold elements is strictly more powerful than a single polynomial threshold element.

2.5 Publications on Neural Networks Resulting from Grant Support

Published

- J. Bruck and J. Sanz, "A study on Neural Networks", *International Journal of Intelligent Systems*, Vol. 3, pp. 59-75 (1988).
- J. Bruck and J.W. Goodman, "A generalized convergence theorem for neural networks", *IEEE Trans. on Info. Theory*, Vol. 34, pp. 1089-1092 (1988)
- J. Bruck and J.W. Goodman, "On the power of neural networks for solving hard problems", *Journal of Complexity*, Vol. 6, pp. 129-135 (1990).
- J. Bruck and M. Blaum, "Neural networks, error correcting codes and polynomials over the binary n-cube", *IEEE Trans. on Info. Theory,* Vol. 35, pp. 976-987 (1989).
- J. Bruck, "Harmonic analysis of polynomial threshold functions", *SIAM Journal on Discrete Mathematics*, Vol. 3, pp. 168-177 (1990).
- J. Bruck and V.P. Roychowdhury, "On the number of spurious memories in the Hopfield model", *IEEE Trans. on Info. Theory*, Vol. 36, pp. 393-397 (1990).
- J. Bruck, "On the convergence properties of the Hopfield model", *Proc. IEEE*, Special Issue on Neural Networks, Vol. 78, pp. 1579-1585 (1990).
- J. Bruck, *Computing with networks of threshold elements*, Ph.D. Thesis, Department of Electrical Engineering, Stanford University (1989).

3.0 Fundamental Properties of Optical Interconnections

The work in this area was again purely theoretical, and focused on fundamental properties of various interconnect technologies, including optical interconnects, normally conducting electrical interconnects, and superconducting electrical interconnects. Results in the area of thermal limitations of electrical interconnects were also obtained. The work in this area was carried out by Mr. Haldun Ozaktas, who will receive his Ph.D. degree this June. Mr. Ozaktas has not yet accepted a job following his Ph.D. conferral. A summary of the major contributions follows.

3.1 Interconnect Dominated Model of Computation

- Developed a basic theory governing wireability limitations to system size. Showed that wiring area ultimately limits the minimum size of two-dimensional systems.
- Determined heat removal limitations to system size. Showed that heat removal ultimately limits the volume of three-dimensional systems.

3.2 Optical Systems

- Determined a lower bound for the communication volume required for an optically interconnected array of points.
- Examined several different interconnect architectures have been proposed for implementation in optics. The multifacet holographic interconnect architecture (based on free-space propagation to a faceted hologram) and the folded multi-facet architecture (based on substrate mode holograms) were shown to have less than optimum two-dimensional growth properties, and an improvement with close to optimum growth in two dimensions was found.
- A three-dimensional multifacet architecture with optimum volume growth properties was also found.
- The optimal electromagnetic carrier frequency that balances metrical information density and heat removal requirements was derived and found to be in the general vicinity of the visible-to-near-IR region of the spectrum.

3.3 Physical Limitations to Communication in Computation

- Determined the fundamental properties of optical, normally conducting electrical, and superconducting electrical interconnections. In particular, the interaction of data rate, latency, and number of processors was explored, based on both wireability and heat removal.
- Examined hybrid interconnect architectures, in which normally conducting electrical interconnects are used for short distance communication, and either optics or superconducting electrical interconnects is used for long distance communication. Determined the optimal partitioning of interconnect technologies in a given computational structure.

- Examined the concept of the all-optical digital computer, in which both the interconnects and the logic elements are optical. Determined the number of processors needed before the all-optical computer is competitive with a hybrid-interconnected electronic computer. Determined the likely characteristics of an all-optical computer, in terms of numbers of processors and volume occupied.
- Examined some indirect implementations of optical interconnects, including the multiplexed grid architecture and the multiplexed fat tree architecture.

Publications on Optical Interconnects Resulting from Grant Support

Published and Accepted:

- H.M. Ozaktas and J.W.Goodman, "Lower bound for the communication volume required for an optically interconnected array of points", *J. Opt. Soc. Am.- A*, Vol.7, pp. 2100--2106 (1990).
- H.M. Ozaktas, Y. Amitai, and J.W. Goodman, "Comparison of system size for some optical interconnection architectures and the folded multi-facet architecture", *Opt. Commun.*, 1991. (Accepted for publication).
- H.M. Ozaktas, Y. Amitai, and J.W. Goodman, "A three dimensional optical interconnection architecture with minimal growth rate of system size", *Opt. Commun.*, 1991. (Accepted for publication).
- H.M. Ozaktas and J.W. Goodman, "The limitations of interconnections in providing communication between an array of points", in Frontiers of Computing Systems Research (Stuart K. Tewksbury, Editor), Plenum Press, New York, 1991. (In Press)

Submitted:

- H.M. Ozaktas and J.W. Goodman, "The optimal electromagnetic carrier frequency balancing structural and metrical information densities with respect to heat removal requirements", *J. Opt. Soc. Am. - A*. (Submitted 1990.)
- H.M. Ozaktas, H. Oksuzoglu, R.F.W. Pease, and J.W. Goodman, "The effect on scaling of heat removal requirements in 3 dimensional systems", *IEEE Electron Dev. Lett.* (Submitted 1990).

In preparation:

- H.M. Ozaktas and J.W. Goodman, "Organization of information flow in computation for efficient utilization of high information flux communication media", (To be submitted to *Applied Optics* or *Optics Communications*.)
- H.M. Ozaktas and J.W. Goodman, "On the usefulness of optical digital computing", (To be submitted to *Applied Optics*.)
- H. M. Ozaktas, *A Physical Approach to Communications Limits in Computing*, Ph.D. Thesis, Department of Electrical Engineering, Stanford University, June 1991.

Conference papers:

- H.M. Ozaktas and J.W. Goodman, "Optimal partitioning of very large scale optoelectronic computing systems", In 1991 Annual Meeting Technical Digest, Optical Society of America, 1990.
- H.M. Ozaktas and J.W. Goodman, "Multiplexed hybrid interconnection architectures", In *Technical Digest of the 1991 OSA Topical Meeting on Optical Computing*, 1991.